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METEORIC FLUX AND DENSITY FIELDS ABOUT AN INFINITESIMAL ATTRACTIVE CENTER GENERATED BY A STREAM MONOENERGETIC AND MONODIRECTIONAL AT INFINITY

by D. P. Hale and J. J. Wright

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SUMMARY

The meteoric field structure theory previously developed for meteoric streams monoenergetic and monodirectional at infinity, is applied to the problem of a meteoric stream incident upon an infinitesimal attractive center. Flux and density contours about the center are explicitly obtained for a particle speed at infinity of 2 km/sec as an example of a method developed to provide flux and density contours for any speed. An incident stream five to ten earth diameters in width results in an order of magnitude enhancement of flux at points downstream from the attractive center. The flux patterns for any energy can be derived from a universal flux plot in terms of a dimensionless parameter $\lambda = y\,r$ where $y = \frac{V_\infty^2}{\gamma M}$ and r is distance in earth (or center) radii. This universal flux plot is exhibited in the paper.

SECTION I. INTRODUCTION

The broad objectives of this paper are the development of the detailed flux and density meteoric fields generated by an incident meteoric stream, which at infinity is monoenergetic and monodirectional, interacting with an attractive center of finite extent. The fields for the case of an infinitesimal attractive center are also obtained; these are simpler than for the case of the finite center by virtue of the fact that no screened zones can appear.

We feel that this is an important case for attractive centers in the solar system other than the sun, relative to which few meteors possess hyperbolic energies. For bodies of planetary size the situation is different; that is, in some local regions, they do provide the dominant gravitational field; and relative to them, meteoric bodies do possess hyperbolic energies. Thus, in essence, we are assuming that a meteoric stream, whose trajectory is determined almost everywhere by the solar field, nevertheless, in the near vicinity of a planet (e.g., the earth) can be usefully approximated as a stream which relative to the planet was monodirectional-monoenergetic at infinity.

In developing the hypothesis we are not asserting that the capture of, and captured, meteoric particles may not be an existent and important phenomenon; rather, we will demonstrate that monoenergetic-monodirectional streams at infinity constitute one mechanism for the realization of meteoric field patterns exhibiting large and abrupt variations in flux and density. That such variations exist appears to be well established; furthermore, they are required by several theories for the explanation of a wide range of phenomena. Direct counting of meteoric impact rates by means of satellite experiments reveals, within a few hundred kilometers of the earth, flux concentrations [1-6, 19] of dust that are indicated, on the basis of some Zodiacal light-Solar F Corona data, to be orders of magnitude greater than those far from the earth. Moreover, observed impact rates vary rapidly within periods of hours [7-11] but, otherwise, behave as might be expected from concentrated streams.

Possibly of special interest, relative to the application of the theory to be developed here, is the case of dust moving about the sun at a distance of about one A. U. The speed of these particles relative to earth would be quite small and, indeed, would be treated by our theory as possessing speeds relative to the earth, at infinity of a few kilometers per second at the most. Their observed relative velocities would be due principally to a conversion of gravitational geopotential energy. It is precisely these very slow particles which give rise to the most complex meteoric fields about a finite earth. These, of course, are in addition to the small particles of approximately normal distribution in speed reported by Eshleman and Gallagher [12]. Their existence and field patterns might be important in discussions of (1) the Zodiacal light [13], (2) the concentration of fine Ni particles within noctilucent clouds where densities relative to space outside the cloud is greater by orders of magnitude [14, 15], (3) the concentration of condensation nuclei for ordinary rain clouds, and (4) the variation of concentration of dust responsible for the radiance [16] of twilight sky. This last phenomenon (4) apparently is influenced by the position of the moon, an effect formerly thought impossible through the influence of the lunar gravitational field, but which, now viewed in terms of the field patterns for very slow particles (predicted by the theory to follow) may be a significant factor. Furthermore, it is hoped that the results obtained in this study can be profitably applied to the analysis of the data to be obtained from the NASA Meteoroid Measurement Satellite, and especially to the data from satellite meteorite observations made farther from the earth which will measure the energy of the impinging particles.

As in most physical theories, our development has some unrealistic features, viz., we assume an infinitely broad, infinitely persisting, monoenergetic-monodirectional meteoric stream at infinity, incident upon a single attractive center, and derive the flux and density contours for various energies which would result in such a situation. The probable importance of other forces for very fine particles (i. e., radiation pressure, Poynting-Robertson effect, and Coulomb drag) is also recognized; therefore, in situations where these are also prominent, our present development can be considered as preliminary.

Fundamental to this development are the concepts of density, current, and flux. Here, density is simply the number of particals per unit volume. The current at any point is a vector tangent to the particle trajectory, passing through the given point, and pointing in the direction of particle motion; the magnitude of the current vector is chosen equal to the number of particles moving along the trajectory which cross a unit area normal to the trajectory during unit time. The magnitude of the current is the product of the density and particle speed at the point. In situations where a given point may be threaded by trajectories passing in two or more directions, the current concept loses its usefulness. In such cases it may be generalized to the concept of flux which is defined to be the total path length generated or swept out per unit volume in unit time. Flux is a scalar quantity, obtained by adding the magnitudes of the various current vectors passing through the point; in cases where only one trajectory is possible, flux obviously becomes the magnitude of the current.

SECTION II. METHOD AND MODE OF PRESENTATION

Fundamentally this paper is simply a detailed application of the meteoric field structure theory [17] developed for monodirectional-monoenergetic streams at infinity, incident upon an attractive center. They have shown that, about an infinitesimal attractive center, the flux field ϕ (r, θ) at any point specified in the plane by polar coordinates r and θ with origin at the center, is generally given by the addition of two currents. One current may be unscattered flux, the other scattered flux; or both currents may be scattered. The pertinent equations are sufficiently expressed in terms of an impact parameter a, the angle α between the radius vector and the tangent to one of the two trajectories threading every field point in the case of an infinitesimal attractive center, and y defined by

$$y = \frac{V_\infty^2}{\gamma M} , \qquad (1)$$

where γ is the gravitational constant; M is the mass of the attractive center; and V_∞ is the speed of the stream at infinity. If ϕ_∞ is the flux at infinity, then

$$\frac{\phi(r, \theta)}{\phi_\infty} = \frac{a_1}{r^2 \sin\theta \cos\alpha_1} \frac{da+}{d\theta} + \frac{a_2}{r^2 \sin\theta \cos\alpha_2} \frac{da-}{d\theta} , \qquad (2)$$

where the a's and α's are assigned (Table I) according to whether the field point is in the upstream sector (Sector V) [18] where one current is unscattered and the other scattered, or in the downstream sector (Sector III)[1] where both currents scatter in different directions.

Table I

Compatible Set of a's and α's

Sector	a_1	α_1	a_2	α_2
V Unscattered & Scattered Flux	a_+	$\alpha_+(a_+)$	a_-	$\alpha_-(a_-)$
III Scattered Only	a_+	$\alpha_-(a_+)$	a_-	$\alpha_-(a_-)$

where

$$a_{\pm} = \frac{ry \sin\theta \pm \sqrt{r^2 y^2 \sin^2\theta + 4yr(1-\cos\theta)}}{2y} \tag{3}$$

$$\frac{da_{\pm}}{d\theta} = \frac{1}{2}\left[r\cos\theta + \frac{r^2 y \cos\theta \sin\theta + 2r\sin\theta}{2ya_{\pm} - ry\sin\theta}\right] \tag{4}$$

and

$$\cos\alpha_{\pm} = \pm\left[\frac{r^2 y^2 + 2ry - y^2 a^2 \pm}{r^2 y^2 + 2ry}\right]^{\frac{1}{2}}, \tag{5}$$

where the α's are shown as functions of a's, their associated impact parameters the actual function being exhibited in Equation 5.

The ultimate objective is to present flux and particle density data in the form of isoflux and isodensity contours about the attractive center. Certain

1. The reason for the assignment of numerals V and III is for compatibility with a subsequent paper where the discussion is extended to the case of the finite attractive center.

general features of these plots require detailed explanation. One of these is the $\theta_{k\ max}$ surface, referred to in the plane,[1] as the $\theta_{k\ max}$ line. For the whole continuum of trajectories about the attractive center, this surface is simply the locus of points of perigee. Before crossing the $\theta_{k\ max}$ surface, a trajectory is unscattered; after crossing the surface, the trajectory is scattered (i.e., receding from the center). Both the contours and gradients of both flux and density are continuous upon crossing the $\theta_{k\ max}$ surface; in the case of the finite scattering center, there are surfaces for which this is not true. Thus, for a stream incident upon the earth, with a particle speed $\geq$ 5 km/sec, the associated $\theta_{k\ max}$ surface divides all space about the center into two sectors; that is, this surface is the boundary between Sector I and Sector II (p. 11 of [18]).

Flux contours were obtained by first holding θ constant in Equation 2 and calculating ϕ as a function of r for a given value of y (effectively, the energy). Performing this for various angles, a series of radial profiles was then plotted; a typical set of profiles is shown in Figure 1. Then, for a fixed value of ϕ, pairs of (r, θ) values can easily be read. The set of (r, θ) values for a given ϕ value defines a flux contour.

Once we have the isoflux contours, density contours can be found by dividing the flux values at the field by the stream speeds; that is, ϕ is essentially the path length swept out in unit volume during unit time. or

$$\phi \equiv \sum_i \rho_i V_i \,, \tag{6}$$

where the summation is over the currents traversing the unit volume. Each current, by carrying a cylinder of unit base of height V_i, and particle density ρ_i through a unit volume during unit time, generates an amount of path length within the unit volume equal to $\rho_i V_i$. Since in our problem V_i depends only on the location of the field points,

$$\phi = \sum_i \rho_i V_i = V \sum_i \rho_i$$

or

$$\rho(r) \equiv \sum \rho_i = \frac{\phi}{V(r)} \tag{7}$$

where the total particle density has been defined to be the sum of the densities arising from the various currents.

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1. This problem is axially symmetric throughout. The actual true dimensional field patterns can, in all cases, be generated by rotating the two dimensional plots about on axis through the center and parallel to V_∞.

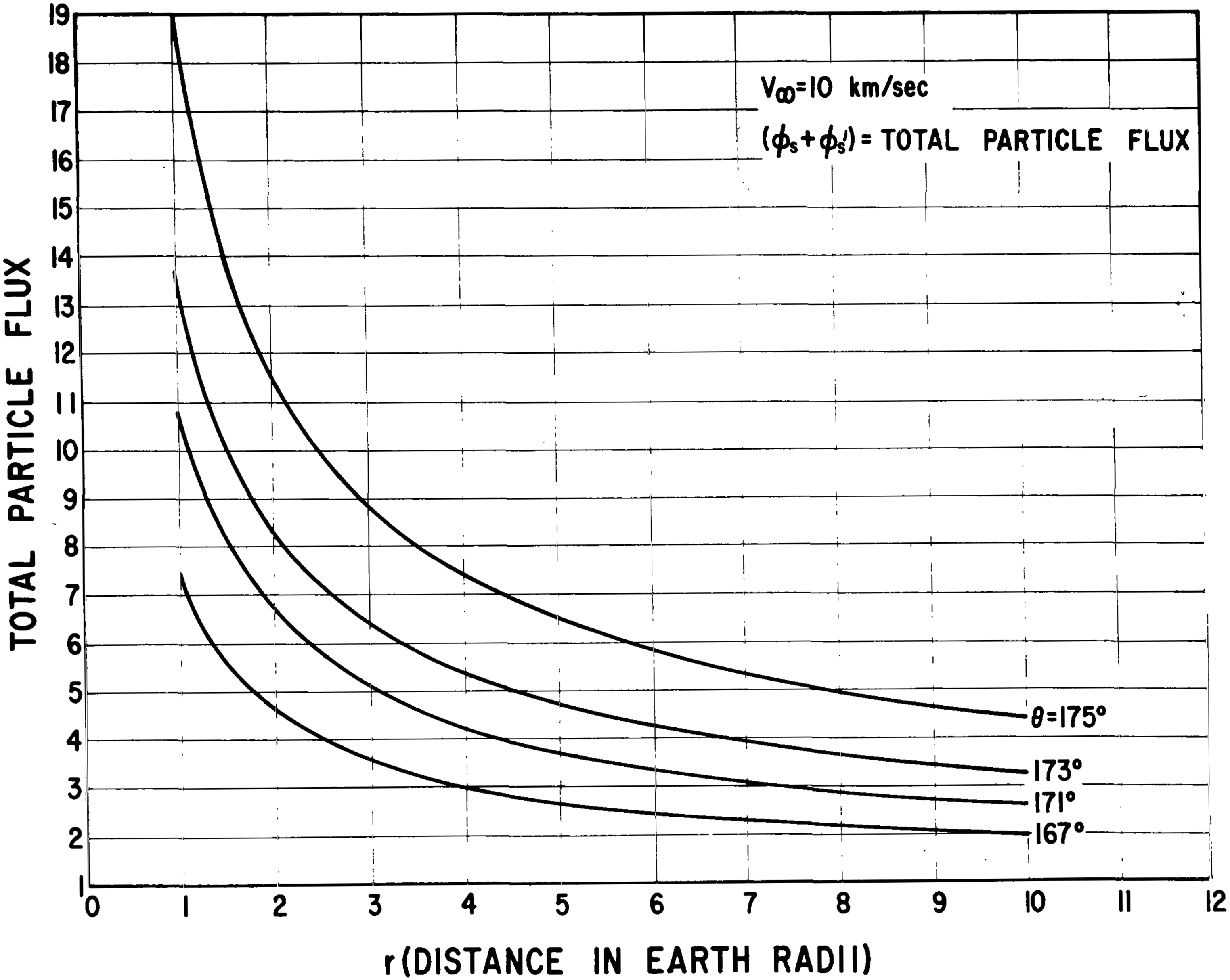

FIGURE 1. RADIAL PROFILES OF TOTAL PARTICLE FLUX FOR $V_\infty = 10^4$ m/sec

SECTION III. FLUX THROUGH UNIT AREA AS $\theta \rightarrow \pi$, $r \rightarrow \infty$

It is obvious, upon inspection of Equation 2, that the flux approaches infinite values as $\theta \rightarrow \pi$. This, however, is a trivial singularity since, upon integration the total flux, threading any finite area containing the axis $(\theta = \pi)$ is always finite at any finite point.

In Figure 2, $\hat{t}$ is a unit vector along one of the trajectories threading the unit area dA, represented by the unit vector $d\hat{A}$. Define $\bar{I}_\pi$ to be the magnitude of the total current passing through $d\hat{A}$, and consider

$$\lim_{\theta \rightarrow \pi} \left\{ \frac{2a}{r^2 \sin\theta \cos\alpha} \frac{da}{d\theta} \hat{t} \cdot d\hat{A} \right\} \equiv \bar{I}_\pi \equiv \frac{\bar{\phi}_\pi}{\phi_\infty} , \tag{8}$$

where it is to be understood that r exceeds by orders of magnitude the unit length, thereby justifying the replacement of the integration by simply multiplying the flux density by the projected area; the factor of 2 arises from the symmetry of particle trajectories near the axis (i.e., $\phi_S \rightarrow \phi_S'$ as $\theta \rightarrow \pi$, and barred quantities are averaged values over the surface element $d\hat{A}$). Using

$$\lim_{\theta \rightarrow \pi} \begin{cases} a \rightarrow \sqrt{\dfrac{2r}{y}} \\[2ex] \dfrac{da}{d\theta} \rightarrow -\dfrac{r}{2} \end{cases}$$

and

$$\sin\theta = \sin(\pi - \theta) = \sin\epsilon = \epsilon,$$

we have

$$\bar{I}_\pi \rightarrow -2 \sqrt{\frac{2r}{y}} \frac{r}{2} \frac{\hat{t} \cdot d\hat{A}}{r^2 \epsilon \cos\alpha} , \tag{9}$$

where the minus sign denotes diverging flux and $\cos\alpha$ is finite and monotonically approaching unity as $r \rightarrow \infty$. Next, consider

$$1 \equiv \left| d\hat{A} \right| = \pi r^2 \sin^2(\pi - \theta) \simeq \pi r^2 \epsilon^2 , \tag{10}$$

yielding

$$\epsilon \simeq \frac{1}{r\sqrt{\pi}} .$$

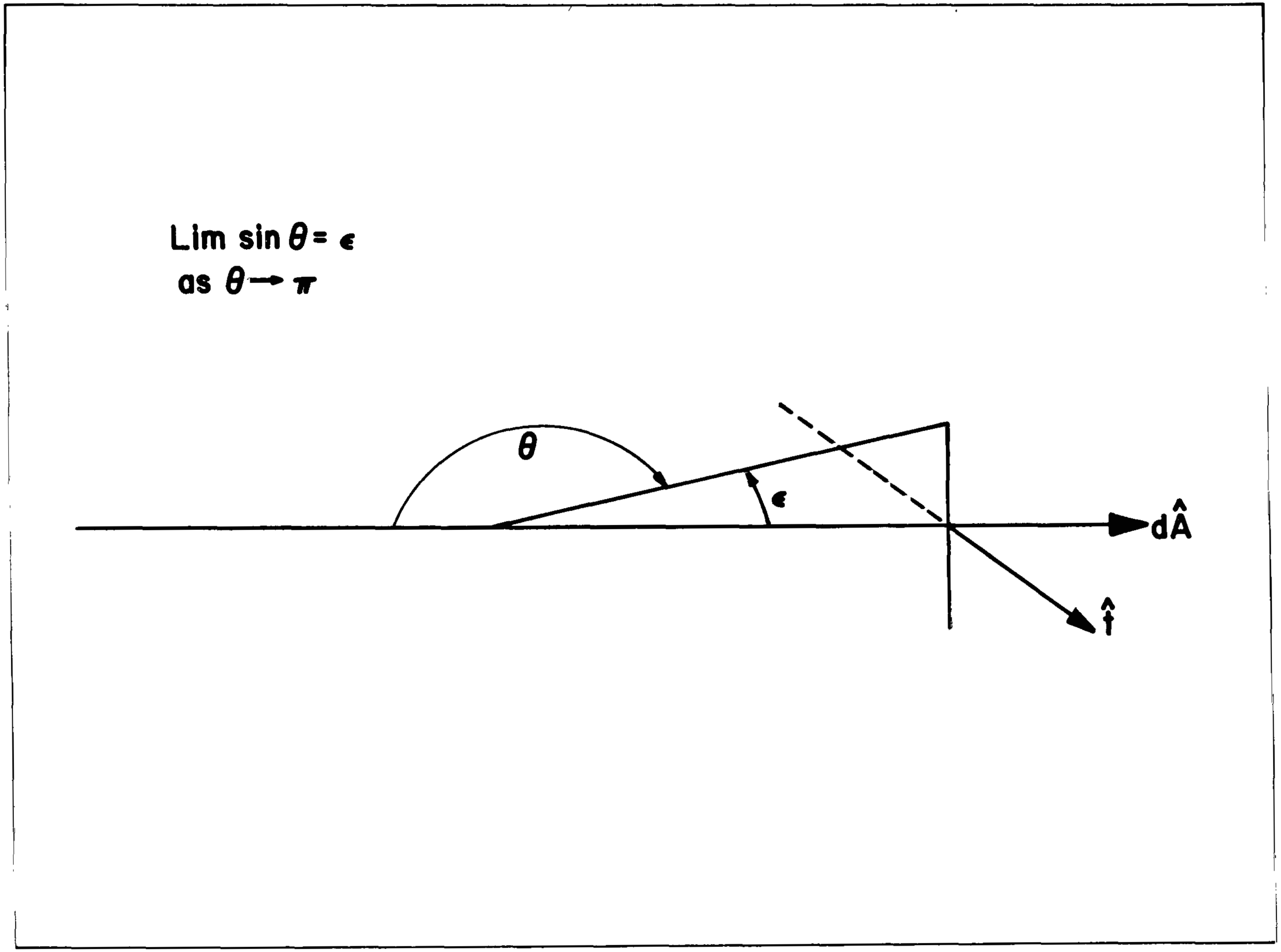

FIGURE 2. GEOMETRY IN VICINITY OF $\theta = \pi$

Since $\hat{t} \cdot d\hat{A} = \cos\alpha$, and substituting for $\hat{t} \cdot d\hat{A}$ and ϵ, we find

$$\overline{I}_{\pi} = \lim_{\theta \to \pi} \frac{\phi}{\phi_{\infty}} = -\sqrt{\frac{2r}{y}}\ \frac{r(r\sqrt{\pi})}{r^2} = -\sqrt{\frac{2\pi r}{y}} = -\sqrt{\frac{2\pi r \gamma M}{V_{\infty}^2}} \tag{11}$$

for flux through unit area on the axis.

For any angle $\theta \neq \pi$, and r approaching infinity, one merely has to substitute in Equation 2

$$\lim_{\substack{r \to \infty \\ \theta \neq \pi}} \begin{cases} a_- \to 0 \quad a_+ \to r \sin\theta \\ \dfrac{da_-}{d\theta} \to 0 \quad \dfrac{da_+}{d\theta} \to \dot{r} \cos\theta \\ \cos\alpha_- \to -1 \ \cos\alpha_+ \to \cos\theta \end{cases}$$

to see that the contribution from scattered radiation (corresponding to a_-) vanishes at infinity as it should, leaving

$$\overline{I}_{\theta} \equiv \lim_{\substack{r \to \infty \\ \theta \neq \pi}} \frac{\Phi}{\phi_{\infty}} = \frac{r^2 \sin\theta \cos\theta}{r^2 \sin\theta \cos\alpha}\ \hat{t} \cdot d\vec{A} = \cos\theta\ , \tag{12}$$

which is exactly what one would expect — this being the result for an undisturbed flux incident upon a unit area whose normal is inclined at direction $(\pi - \theta)$ with respect to the radiation stream.

SECTION IV. UNIVERSAL FLUX PLOT FOR A MONOENERGETIC-MONODIRECTIONAL STREAM INCIDENT ON AN INFINITESIMAL ATTRACTIVE CENTER

Intuitively, one feels that with the exception of a scale factor, the flux field pattern about an infinitesimal attractive center should be independent of energy. This will be shown to be true. At any point about an infinitesimal attractive center, the total flux density consists of two of three possible components, the pertinent pair depending upon, in which of the two spherical sectors the point is located. Field points in the upstream sector have flux contribution from direct (unscattered)flux ϕ_D and from flux scattered into the sector from the other hemisphere ϕ_S'(scattered); field points in the downstream sector have flux contribution from flux scattered from the same hemisphere ϕ_S(scattered) and ϕ_S'(scattered). Thus, in general, the total flux

$$\phi = \sum_{i=S \text{ or } D, S} \left| \phi_i \right| = \sum \left| \frac{a_i}{r^2 \sin\theta \cos\alpha_i} \left(\frac{da_i}{d\theta}\right) \right| . \tag{13}$$

the quantities ya, $y \frac{da}{d\theta}$ and cos α upon explicit exhibition seem to be functions of θ and yr. Defining

$$yr = \lambda , \tag{14}$$

it follows that

$$\phi = \sum_i \left| \frac{ya_i}{y^2 r^2 \sin\theta \cos\alpha_i} \frac{y\, da_i}{d\theta} \right| = \phi(\theta,\lambda) . \tag{15}$$

Equation 15, under certain restrictions, permits the construction of a universal flux plot so-named because from it one can generate the field about any infinitesimal attractive center for any energy. The results of Shelton, Stern, and Hale [17] show that ϕ_S' contributes to the flux at every point; and that with the exception of sign-diverging flux being negative, one function describes both ϕ_D and ϕ_S. Thus, we have attained a function of λ and θ only, which represents the total flux at any point about an infinitesimal attractive center. One should note, however, that this cannot be done for the net flux where the sign of the contribution is important.

This function $\phi(\lambda, \theta)$ is displayed in Figure 3 plotted against θ, with λ being the parameter for a family of λ = constant curves. For a given angle and specified y — the energy and attractive center strength — and distance, one can readily read off the total flux at that point relative to unit flux at infinity. Alternatively, one may wish to know for a given flux corresponding to a certain energy, at what distance from the center along a given direction (a radial line) will the flux be the same for another energy or attractive center strength. This question led to the idea of a universal plot and is easily answered by considering:

$$\lambda_i = y_i r_i = \frac{V_{i\,\infty}^{\,2} r_i}{\gamma M_i} = \frac{V_{j\,\infty}^{\,2} r_j}{\gamma M_j} = y_j r_j = \lambda_j ,$$

or one might wish to know for a given distance from the center and for a specified energy, that together determine λ, the minimum value of θ for which the flux exceeds a stated value.

Figure 3 includes the following range for an earth mass attractive center (R_E is the earth's radius):

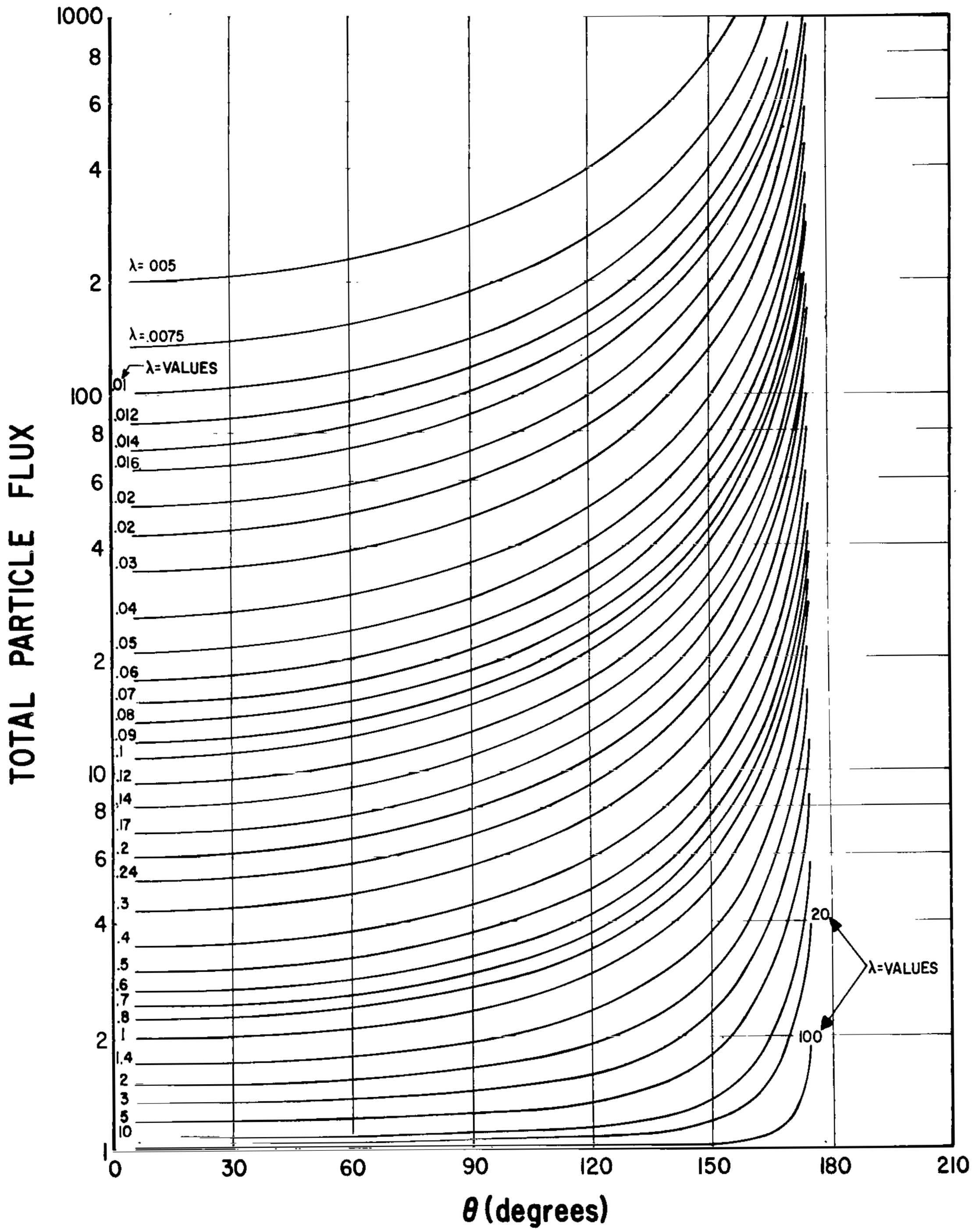

FIGURE 3. UNIVERSAL FLUX PLOTS RELATIVE TO UNIT MONODIRECTIONAL, MONOENERGETIC INCIDENT FLUX AT INFINITY ABOUT AN INFINITESIMAL ATTRACTIVE CENTER IN TERMS OF PARAMETER $\lambda \equiv yr$, WHERE $y = V_\infty^2/\gamma M$ and r = DISTANCE IN EARTH RADII

$$.005 \leq \lambda \leq 100 .$$

(1) For

$$V_\infty = 1 \text{ km/sec}, \quad .3R_E \leq r \leq 6250\ R_E$$

which, of course, far exceeds the space within which the earth's field is effectively the only field, and (2) for

$$V_\infty = 80 \text{ km/sec}, \quad 5 \times 10^{-5}\ R_E \leq r \leq .98\ R_E ,$$

which is within the earth. However, this deficiency at the higher energies is more apparent than real, in that it is evident from Figure 3 that at high energies or great distances ($\lambda > 100$) the flux deviates but very slightly from its value of unity assumed at infinity.

Figure 3 contains a great deal of information about the field. Its main uses can perhaps be best summarized by the tabulations given in Table II:

TABLE II

Interpretations of Universal Plot

	y = constant	r = constant
If ϕ = const.	Line ϕ = const. in Fig. 3 generates a constant ϕ surface (flux contour) in real space	Line ϕ = constant in Fig. 3 generates y values which at the associated points (r, θ) would deliver total flux ϕ
If θ = const.	Line θ = const. in Fig. 3 directly yields flux along radial direction in real space	Line θ = constant in Fig. 3 generates associated y and ϕ values for point specified by θ = constant; r = constant

If λ and r = constant, Figure 3 generates gnomonic plots, i.e., total flux on surfaces of spheres in real space.

$r \cdot y$ = constant (both r and y vary inversely). Then the angle at which perigee occurs, θ_k is specified by $\cos \theta_k = \frac{-1}{1+\lambda}$. Cones with a common vertex at origin are generated in real space, on the surface of which trajectories, associated with y values determine from $y = \frac{\lambda}{r}$, and having impact parameters $a = r(1+\frac{2}{ry})^{1/2}$ [17], attain perigee.

SECTION V. RESULTS AND CONCLUSIONS

Figures 4 and 5 show a sample set of results obtained by the application of the foregoing analysis to the case of $V_\infty = 2$ km/sec. We recognize that such small relative speeds, if they are physically significant at all, will be only for the finest (high magnitude) meteoric dust, and we therefore do not insist on their reality. The assumption that $V_\infty = 2$ km/sec was made because these relatively low energy patterns most strongly display the enhancement effect we desired to establish. This effect also exists at higher energies; the higher energy field patterns have been obtained [18], where, appropriately, we consider a finite attractive center.

Figure 4 shows the total particle flux contours about an infinitesimal attractive center resulting from a monoenergetic-monodirectional stream incident from the left. Total particle flux means that both diverging and converging fluxes have been summed to obtain the final result. Here, as in Figure 5, all flux values have been normalized relative to a value of unity in the incident stream at infinity. The dashed line in the plane of Figure 4 is the $\theta_{k\ max}$ surface or, rather, the surface generated by the loci of points of perigee; flux and density contours and their gradients as well, are continuous upon crossing this surface. It is apparent from Figure 4 that under the assumed conditions, gravitational focusing can cause localized enhancement of flux by orders of magnitude. This effect is far greater than previously expected, many authorities having felt that enhancement factors might possibly be as great as two or three. Furthermore, we hasten to point out that such enhancement can occur quite close to the earth, (earth radii are shown in a scale on Figure 4) and that an incident stream need be only 5 to 10 earth diameters in width to cause an order of magnitude enhancement.

Figure 5 shows total particle density contours about an infinitesimal attractive center for $V_\infty = 2$ km/sec normalized to unit flux in the undisturbed stream. The enhancement in density is less than that for flux, an effect obviously due to the speeding up of particles as they near the center. As energy increases, the enhancement at any given point of both flux and density decreases, and the flux and density enhancements tend toward unity.

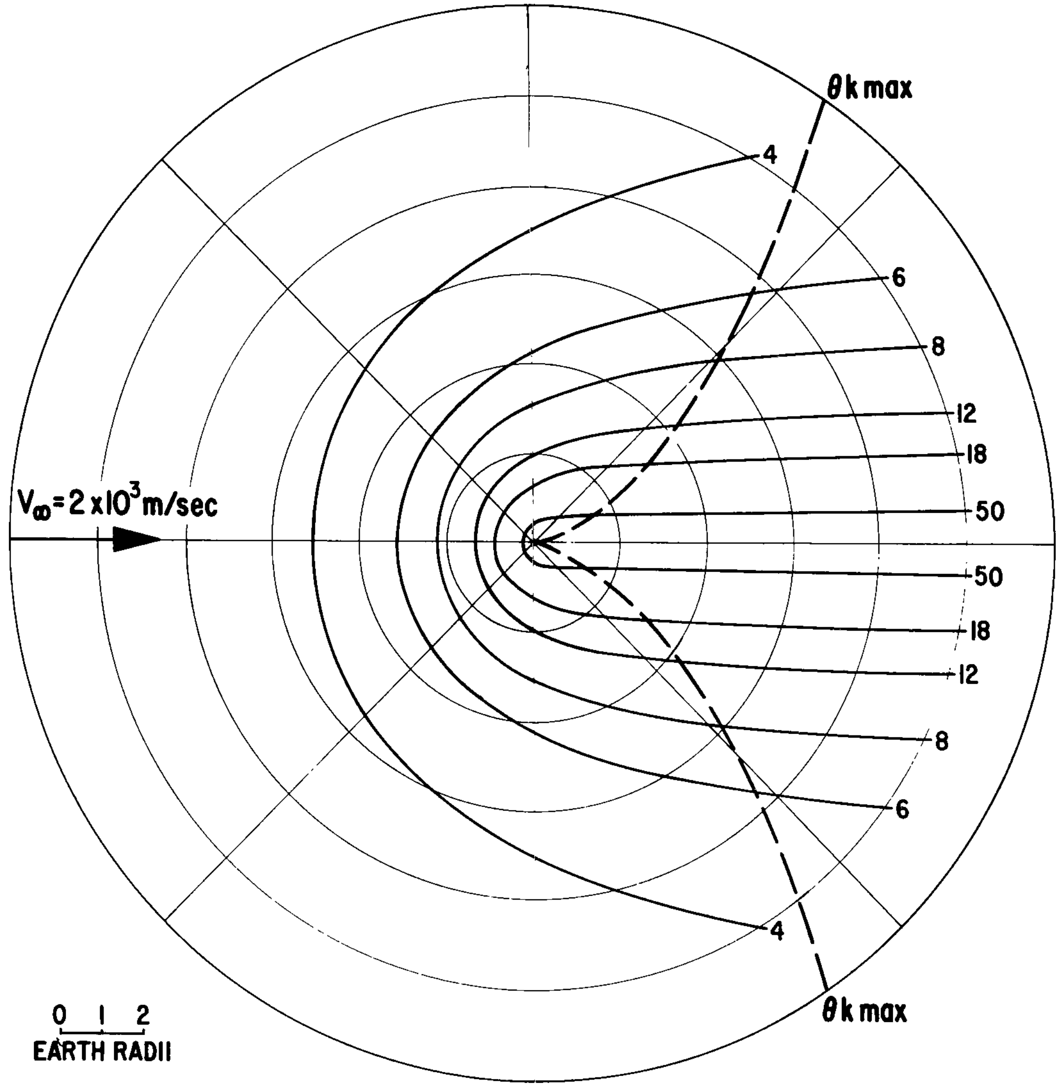

FIGURE 4. TOTAL PARTICLE FLUX CONTOURS ABOUT AN INFINITESIMAL ATTRACTIVE CENTER RELATIVE TO UNIT MONODIRECTIONAL, MONOENERGETIC INCIDENT FLUX AT INFINITY FOR $V_\infty = 2 \times 10^3$ m/sec

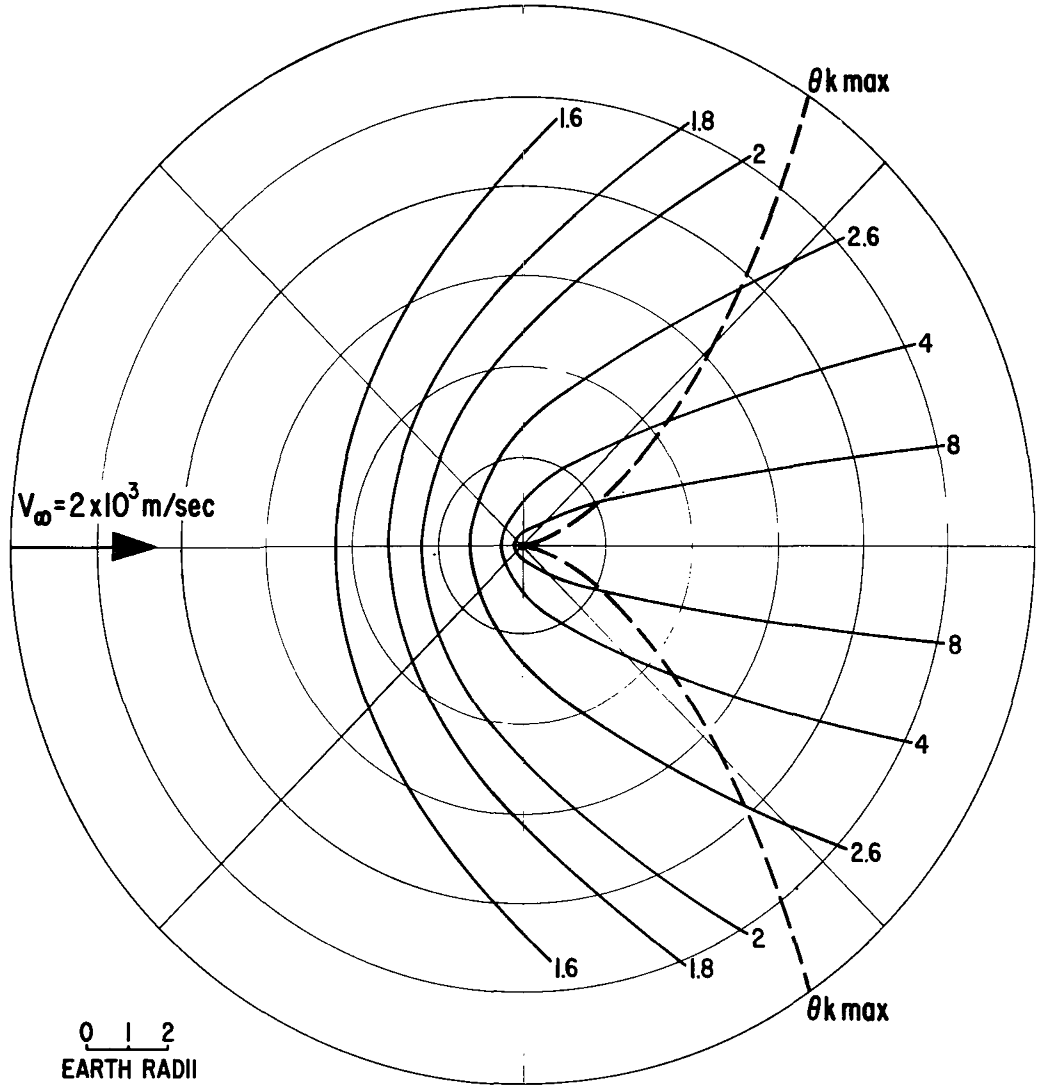

FIGURE 5. TOTAL PARTICLE DENSITY CONTOURS ABOUT AN INFINITESMAL ATTRACTIVE CENTER RELATIVE TO A PARTICLE DENSITY AT INFINITY OF $5 \times 10^{-4} m^{-3}$ ARRIVING FROM A UNIT MONODIRECTIONAL, MONOENERGETIC FLUX AT INFINITY FOR $V_{\infty} = 2 \times 10^3 m/sec$

Figure 3 is the universal flux plot discussed in the foregoing section. Essentially, it is an exploitation of the fact that regardless of the strength of an infinitesimal attractive center of of the magnitude of V_∞, the flux field pattern is unaltered except for a change of scale in distance. The variable λ, the product of r and y, is the basic parameter in this plot. Thus, if at a point distant r from the center in a direction of 150° relative to the radiant of the incident stream, the flux is 6 (corresponding to $\lambda = .8$). It is immediately seen from Figure 3 that if the energy is quadrupled (corresponding to $\lambda = .2$), the new flux at this point will be 20, assuming all flux values to be unity at infinity.

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